Site characterization using joint reconstruction of disparate data types

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Presented by

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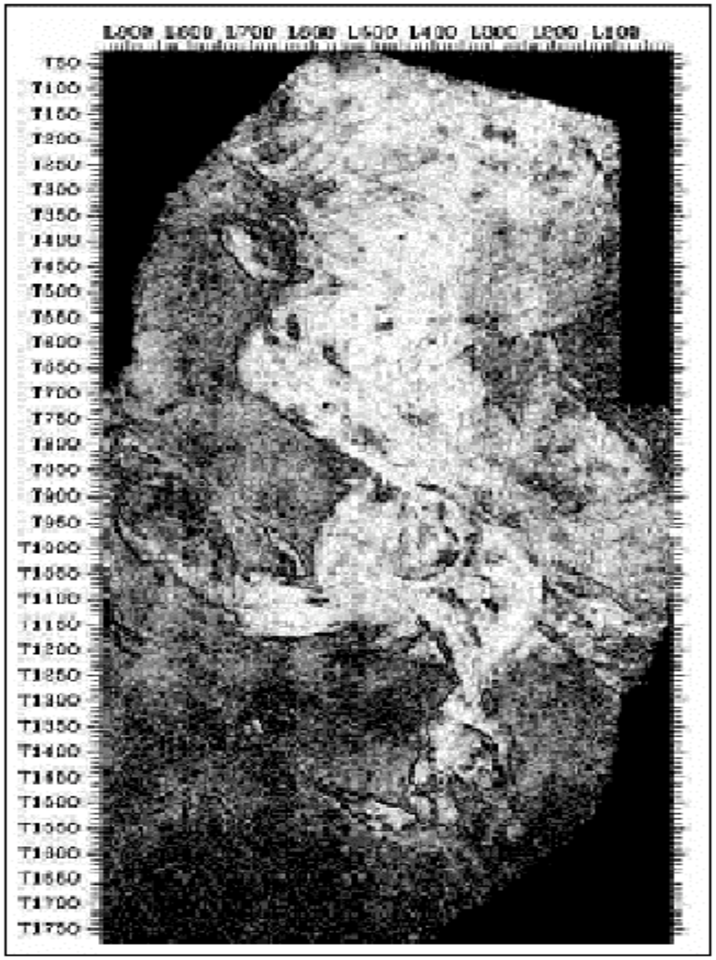
Site characterization, CO_2 storage, and risk assessments are underlain by geological uncertainty

- **What is the geological uncertainty?**
  Are there fast-paths in the reservoir?

  Does a fault transmit fluids or segment a reservoir into compartments?
- **How can one integrate data streams to understand reservoir performance?**
- **Can one reduce uncertainty?**
  How can 4D seismic, injection volumes, and production data constrain uncertainty

In Salah Project, Kretchba field



From Rittiford et al., 2004

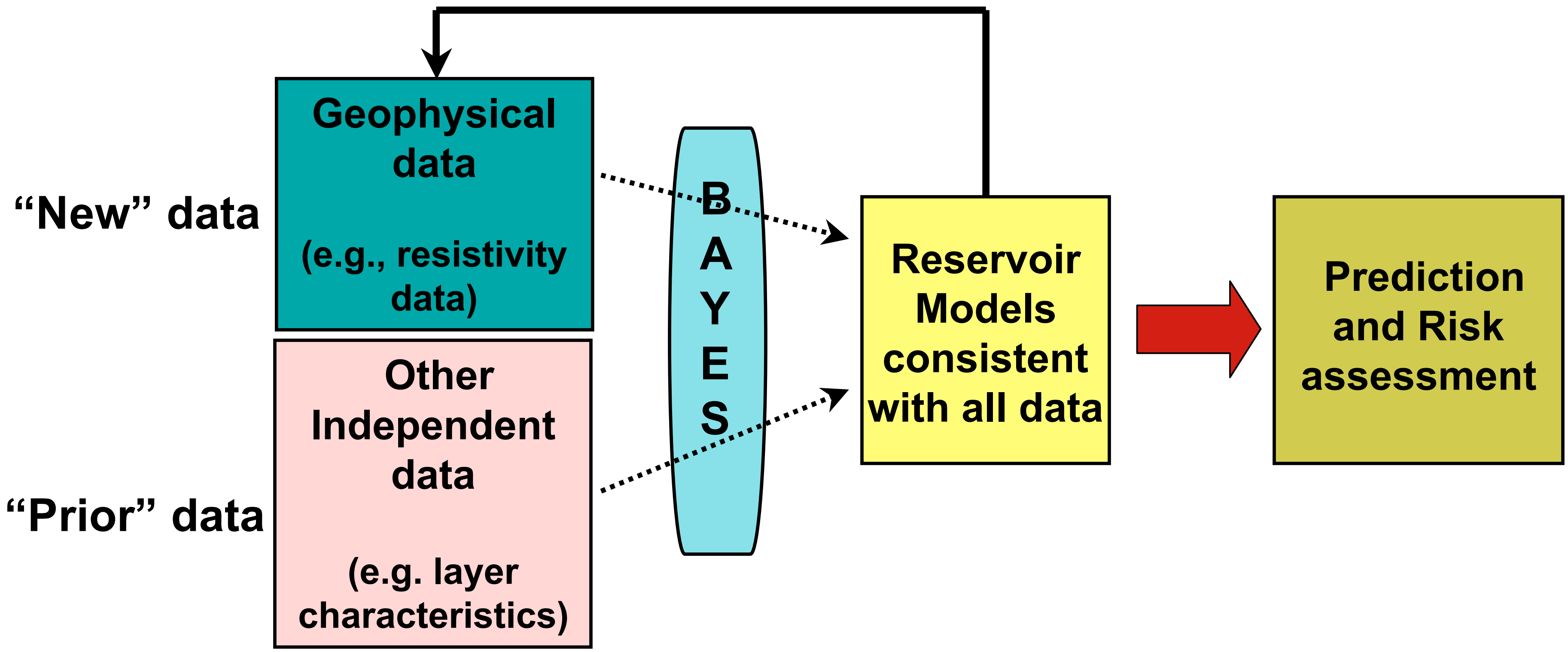
Method for the subsurface imaging of reservoirs and CO_2 plumes

- **Monte Carlo Markov chain (MCMC):**
  - uses disparate data types: integration of data
  - Core logs, geophysical logs, injected CO_2 volume
  - Formation geostatistical trends: correlation length, thickness & juxtapositional tendencies
  - Production data, tracer results, surface & cross-borehole geophysics

- **Provides rigorous measure of uncertainty in the subsurface**
  - Minimization of CO_2 storage risks requires knowledge of subsurface uncertainty
  - Unknown reservoir properties, measurement error, lack of sensitivity/resolution of geophysics

- **The output is distribution of likely reservoir models**
  - Alternative models ranked based on how well they fit the data

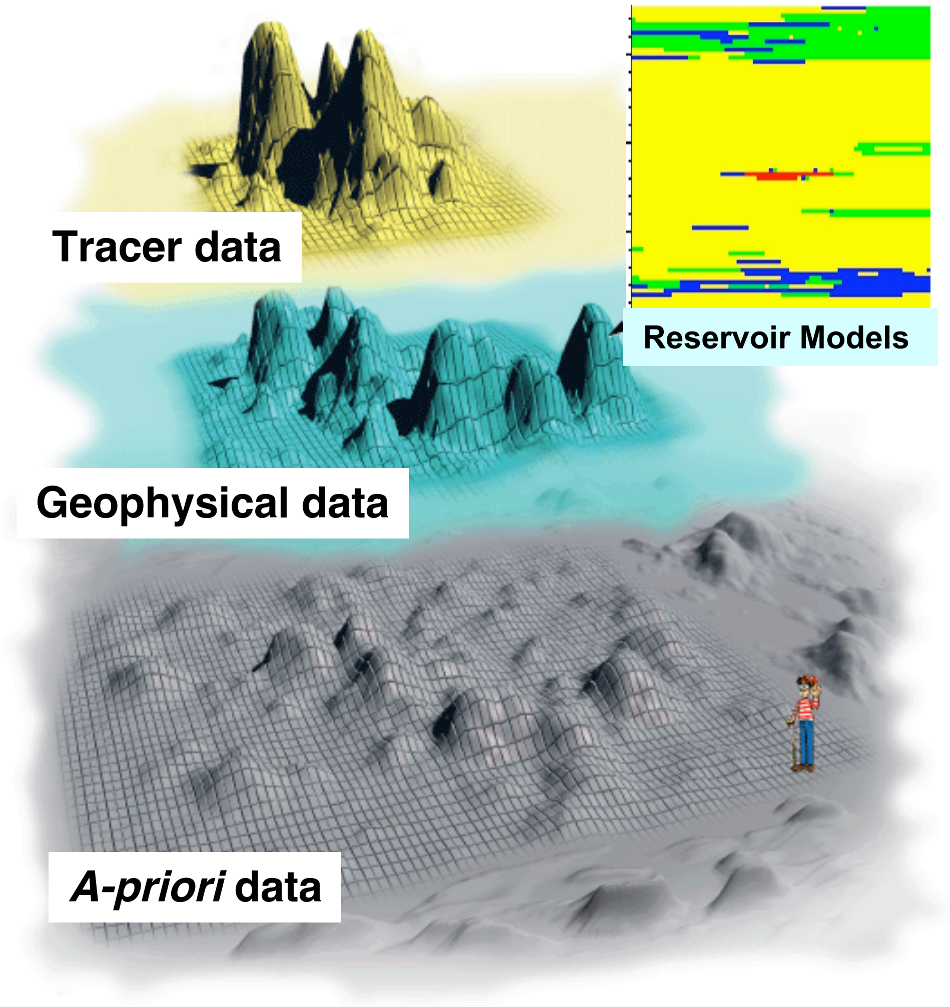
MCMC is a stochastic inversion & data integration approach



The benefits are:

- Rigorously combine geologic & geophysical insight with measurements,
- Measures uncertainty in complex problems,
- Robust – noisy data, solution space with multiple local minima

Goal is to find reservoir models that are consistent with all available data



- Most methods look for the "best" answer
  - -model at the top of the tallest hill
  - - Geophysical inversion is typically non-unique

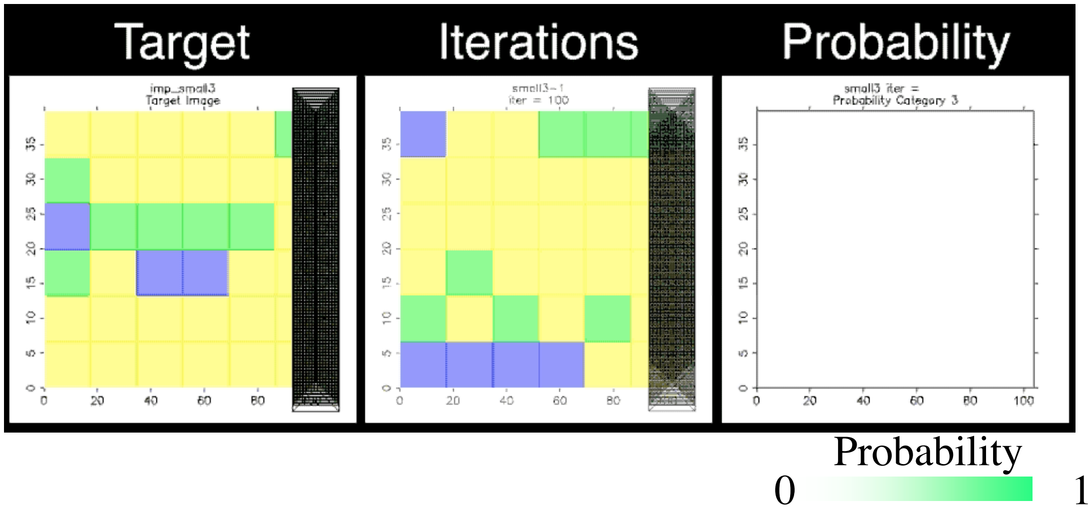
- MCMC :
  - - Identifies alternative models
  - - Alternatives are objectively ranked (hill height)
  - - Measures variability (hill width)

- Joint reconstruction of multiple data increases the height of a few hills
  - - Uses cascade reconstruction approach (Mosegard & Tarantola, 1995)
  - -Reduce uncertainty

Importance Sampling to the Rescue: Rapid Searching of the Good Matches

Random Sampling of Possible Configurations

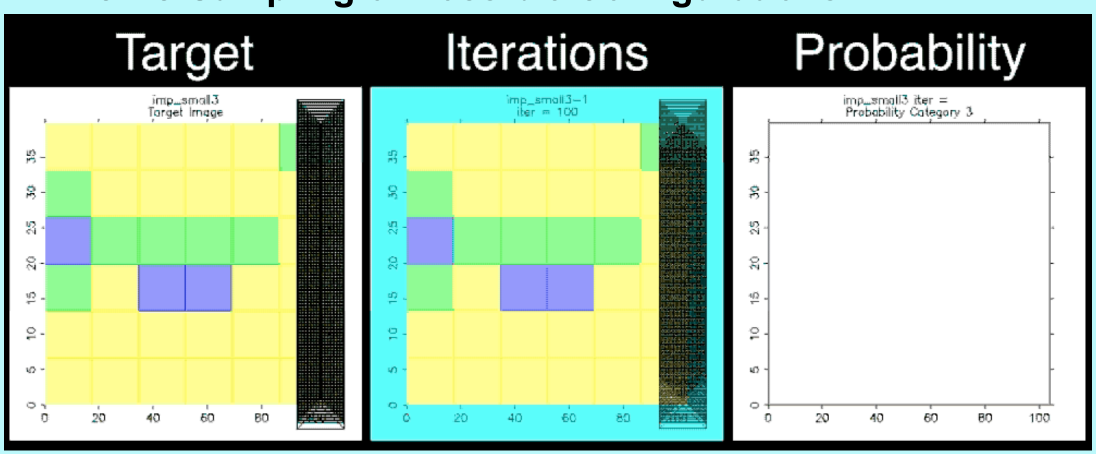
When only random Monte Carlo sampling is used, the true configuration is not found in 700,000 iterations. *(20 trillion possible)*



The stacked sum of random configurations is equal to the prior probability, or the information built into the original lithology model.

MCMC Sampling of Possible Configurations

With importance sampling, the engine repeatedly finds the true configuration (iterations with blue).



The accepted configurations are summed (stacked) to give the posterior probability including error in data and models.

The most probable configuration is repeatedly identified.

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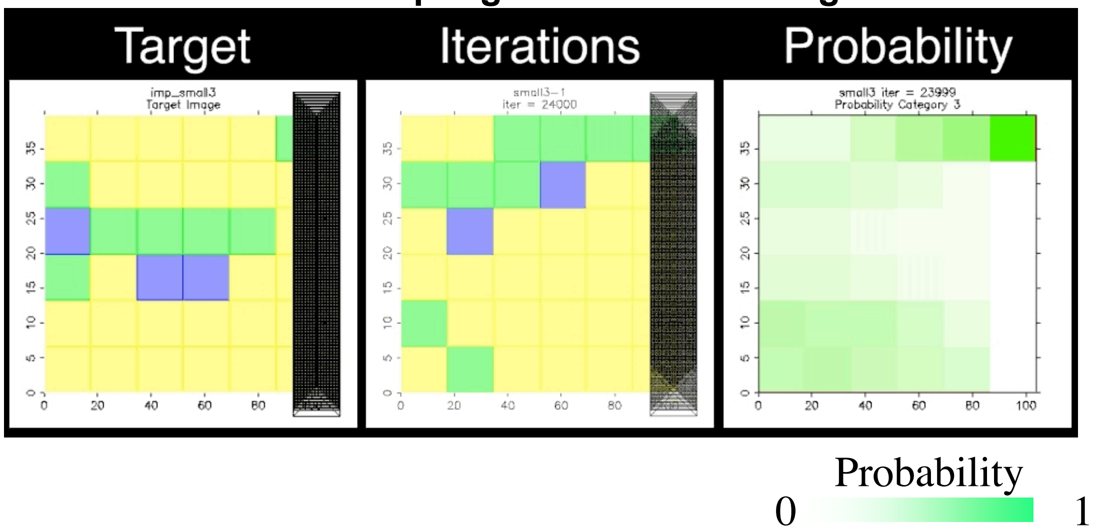

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Stochastic Engine Sampling of Possible Configurations

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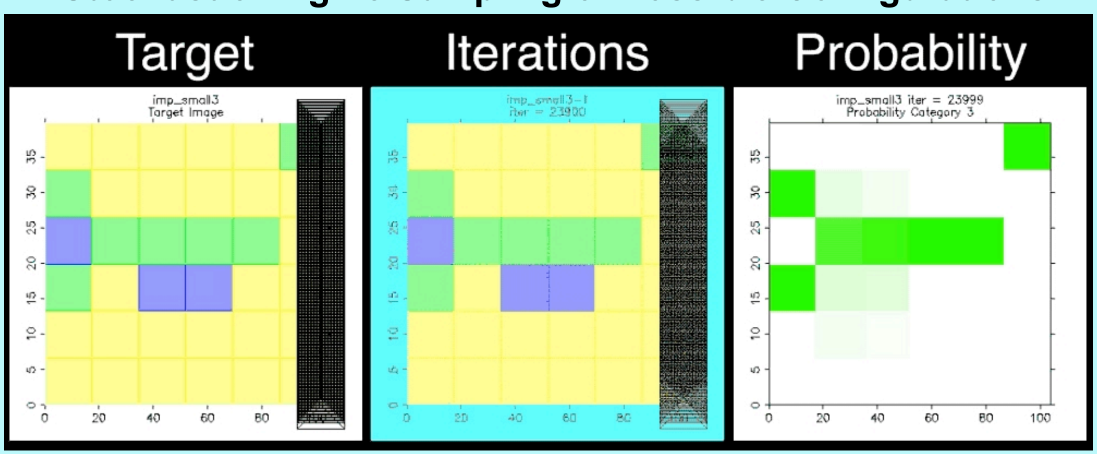

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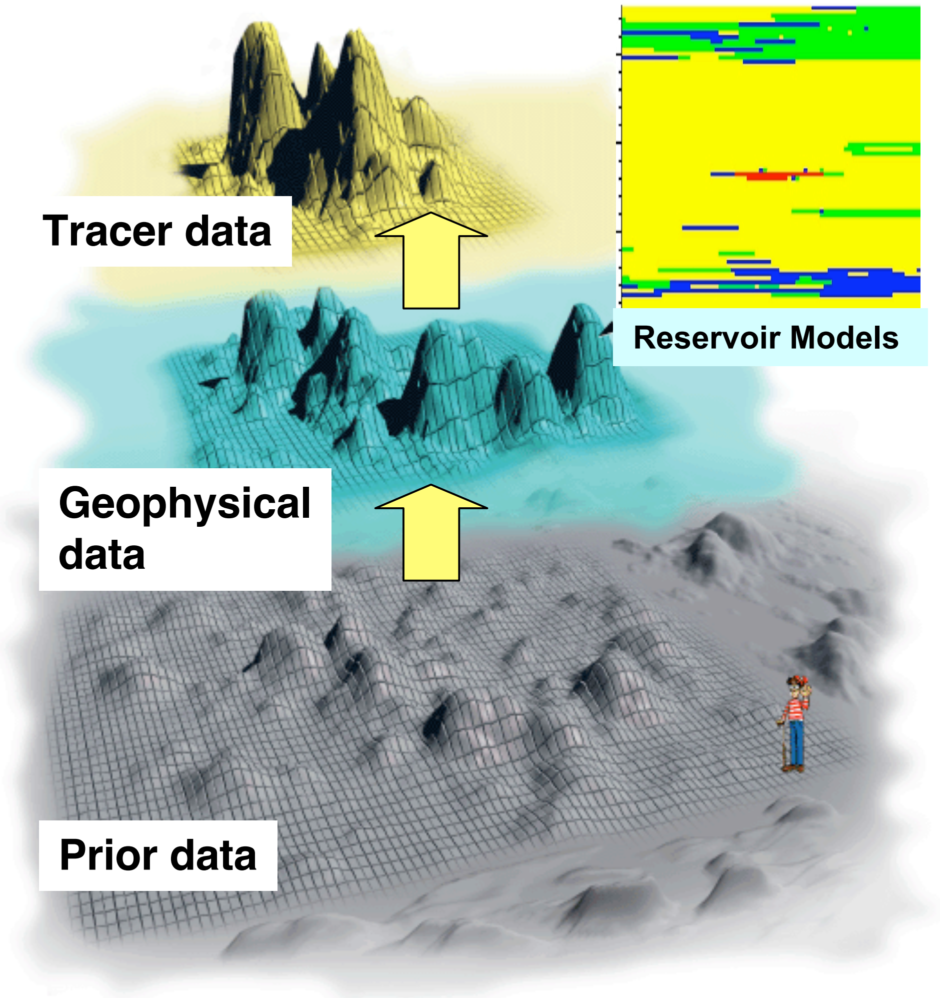
MCMC finds models that are most consistent with the available data



• Prior data: existing core or well-logs, 3-D seismic, formation geostatistical trends, etc.

• Other data could be geophysical measurements, production data, tracer results, etc.

•Tends to hover in regions where models best fit data

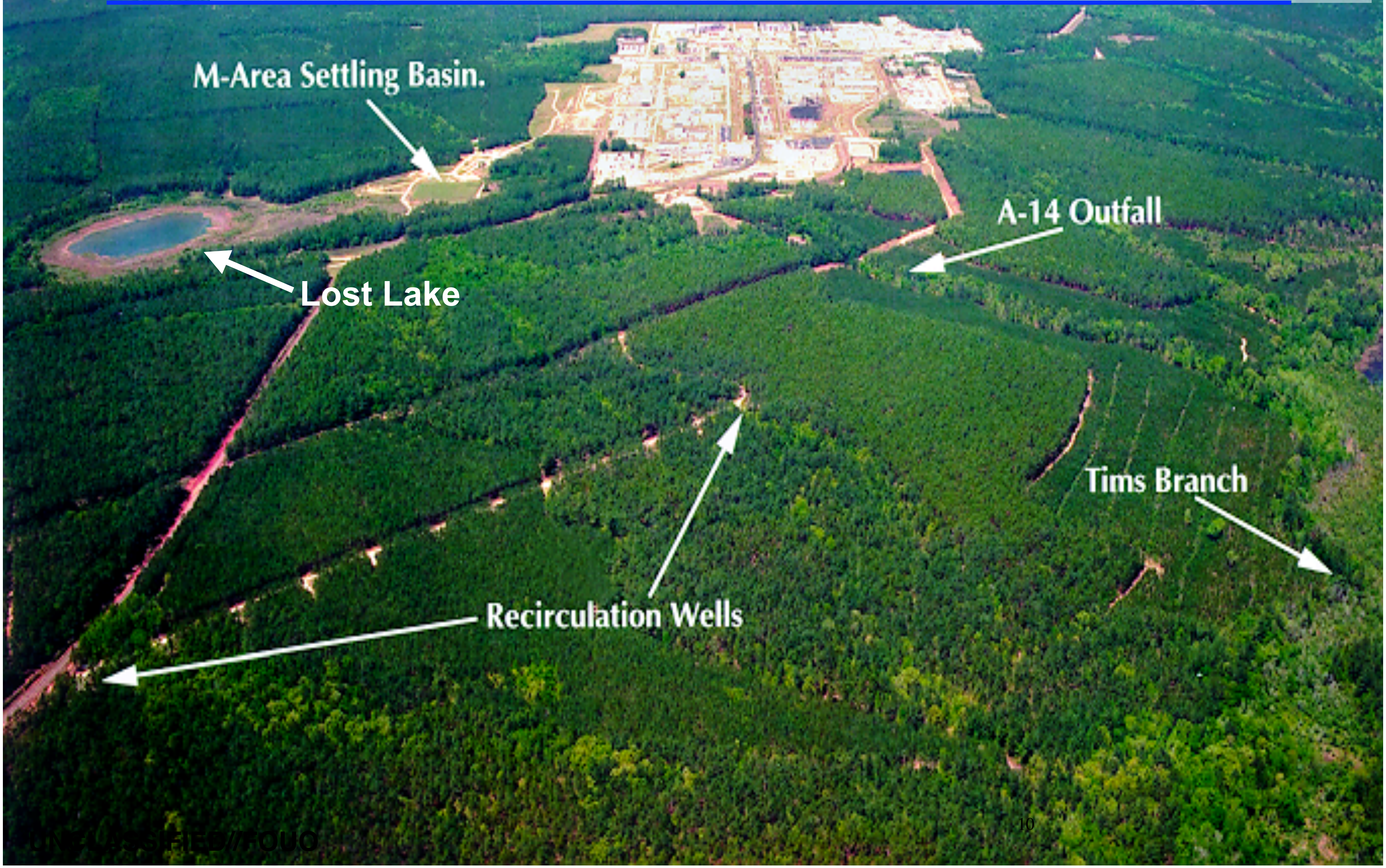
- used to rank alternatives
- much more efficient than conventional Monte Carlo

• Samples the whole space of possible models

- needed to quantify uncertainty
- different from simulated annealing - multiple answers
- computationally intensive

MCMC applied to reservoir characterization

Application: SRS wants to identify contaminant pathways in the A/M area

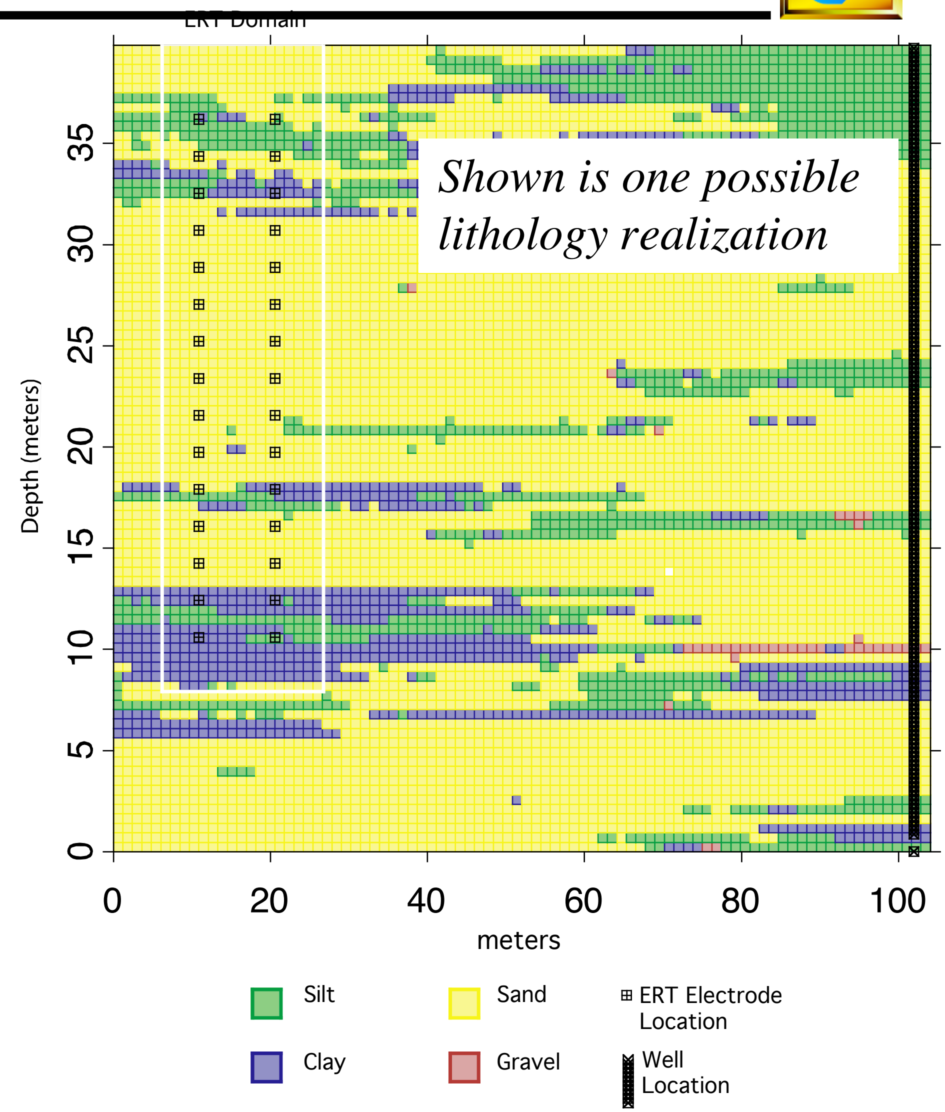


We tested MCMC with data from the Savannah River Site A/M Outfall Area

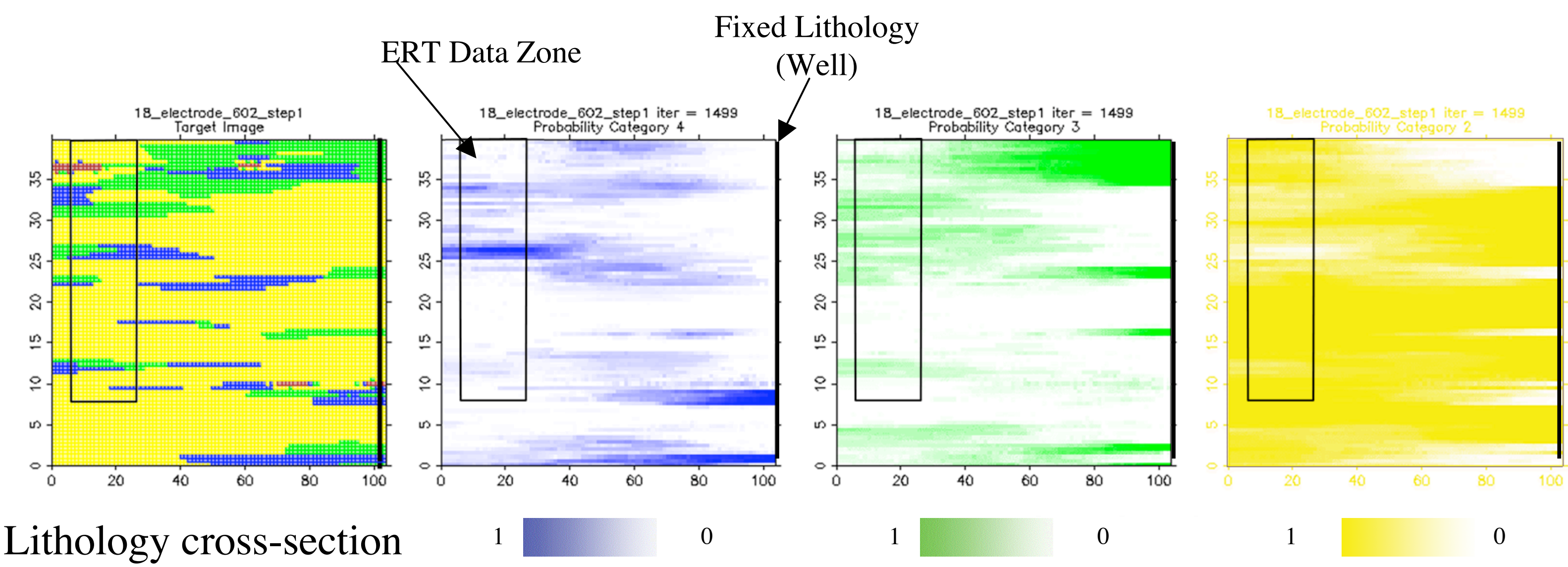
- **Geostatistical Model (Carle et al.) used to generate models**
  - **- Uses borehole data & geospatial trends**
  - **- Correlation lengths, thickness and juxtaposition**

- **Knowns:**
  - **-Lithology at distal well**
  - **- Overall site lithologic trends**
  - **- ERT Data in two wells (poor quality)**

- **Unknowns:**
  - **- Reservoir model away from distal well**



The search found the most likely reservoir models

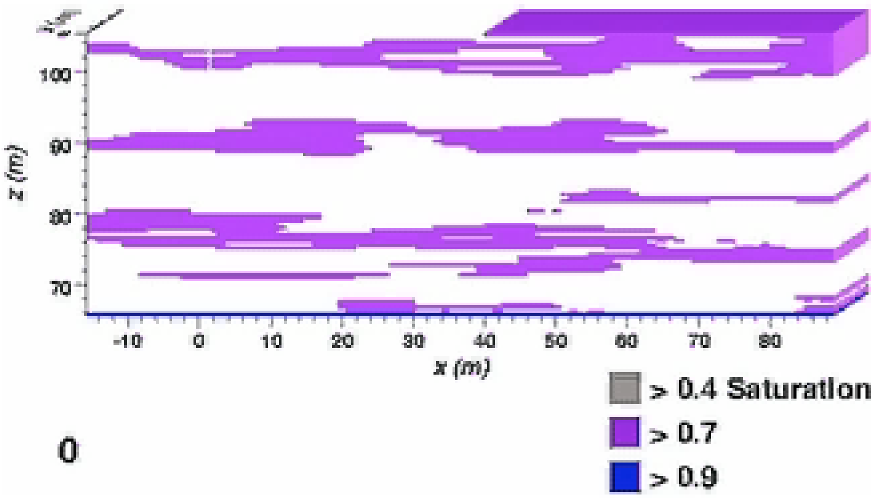


Lithology cross-section (synthetic)

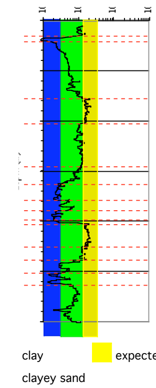
Probability of Each Lithology Type

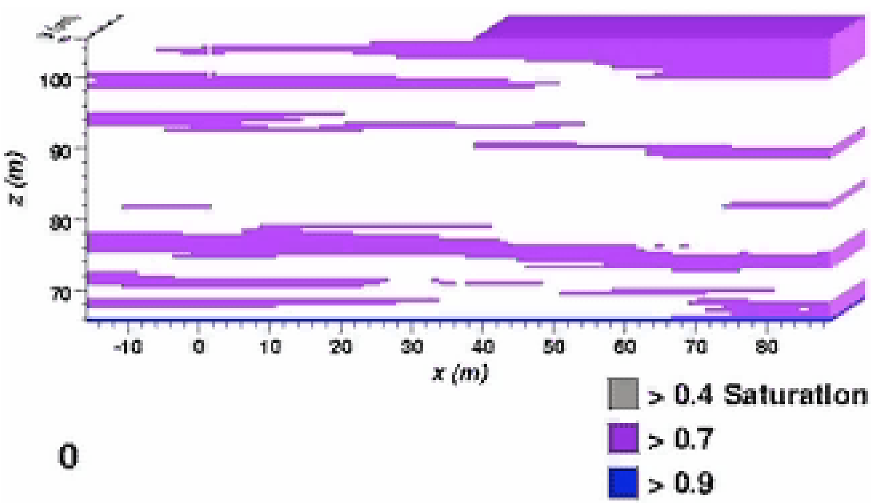
Result: quantitative assessments of uncertainty : useful for risk assessment and site characterization.

Infiltration at the SRS outfall site: the *most likely* differs dramatically from conventional expectation

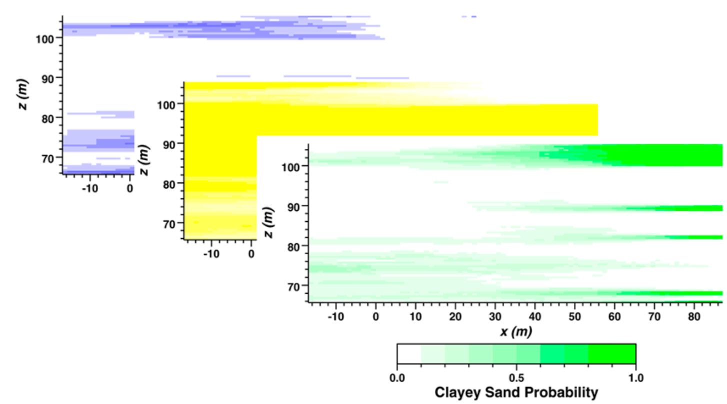


- **Conventional Monte Carlo simulation using the prior geologic data alone predicts fairly uniform infiltration.**





- **Adding the constraints from imaging data results in a very different infiltration pattern; there is a very high probability of a continuous clay layer at 5-10 m.**



Stepwise reanalysis starts with the previous result, which incorporates all previous data and uncertainty.

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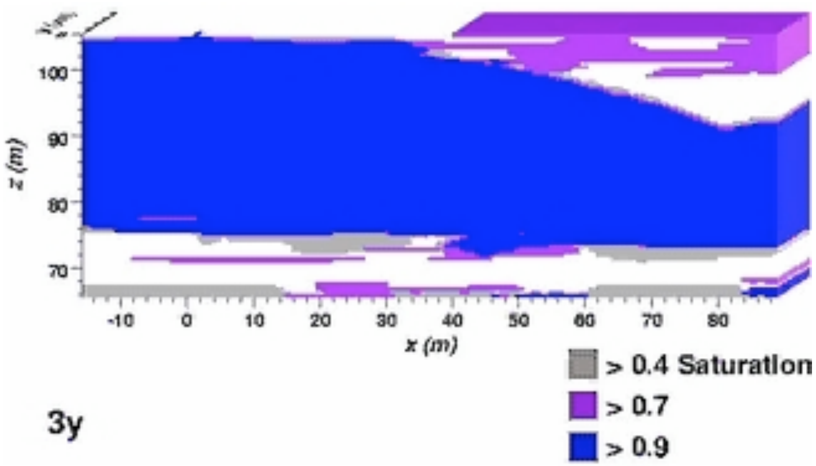

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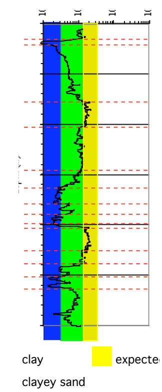

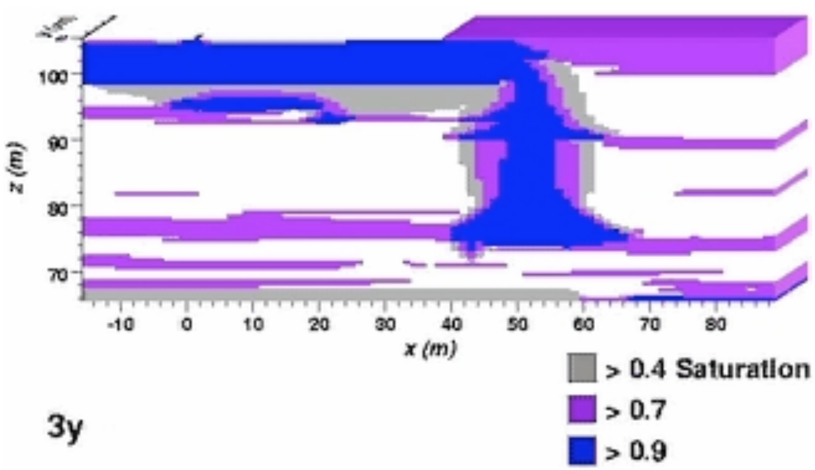

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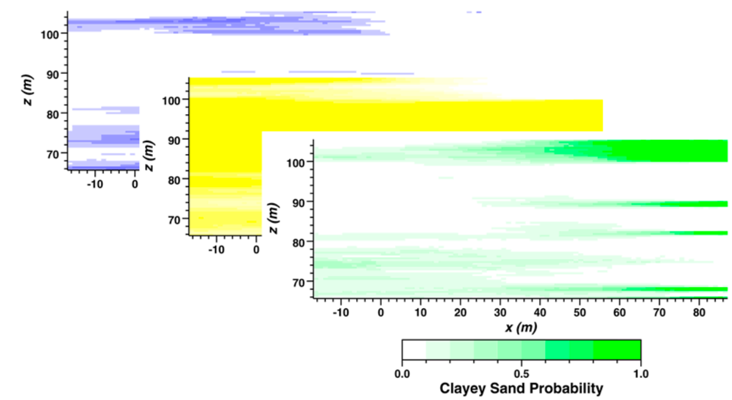

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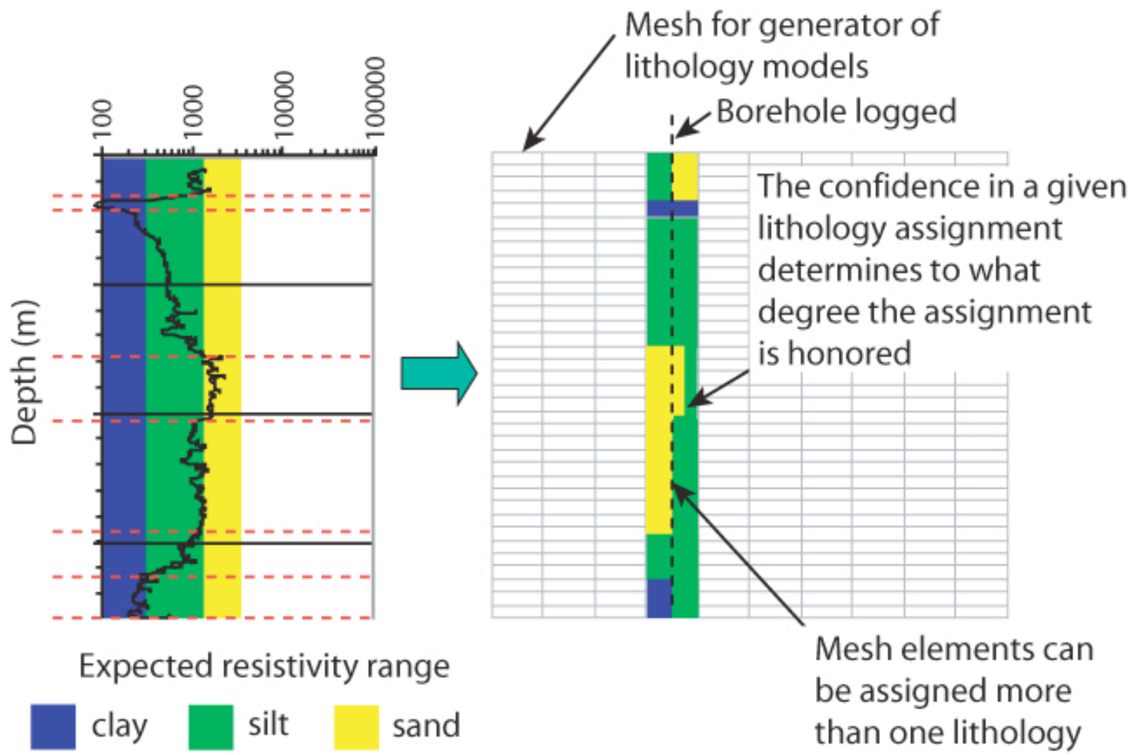
Lithology and geophysical logs are used to constrain the lithology models

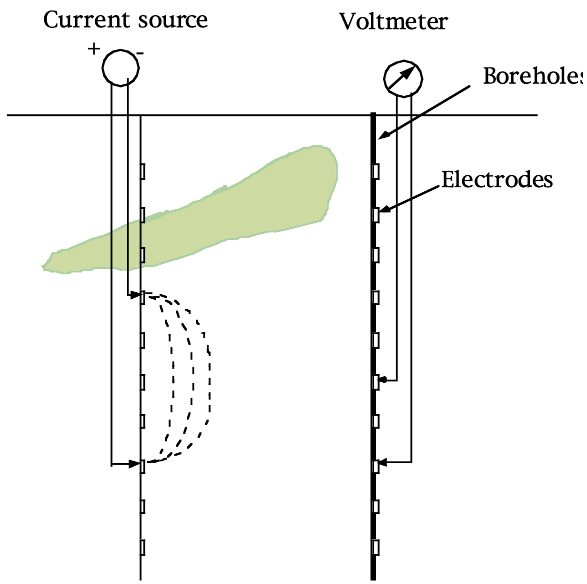
- **Bayesian time-series analysis is applied to establish confidence levels for given lithology types.**

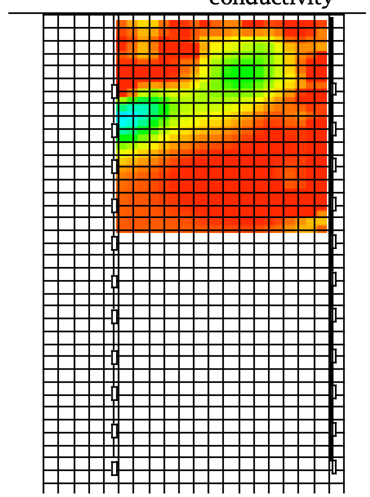
- **This type of "soft" conditioning allows many kinds of data to be incorporated**

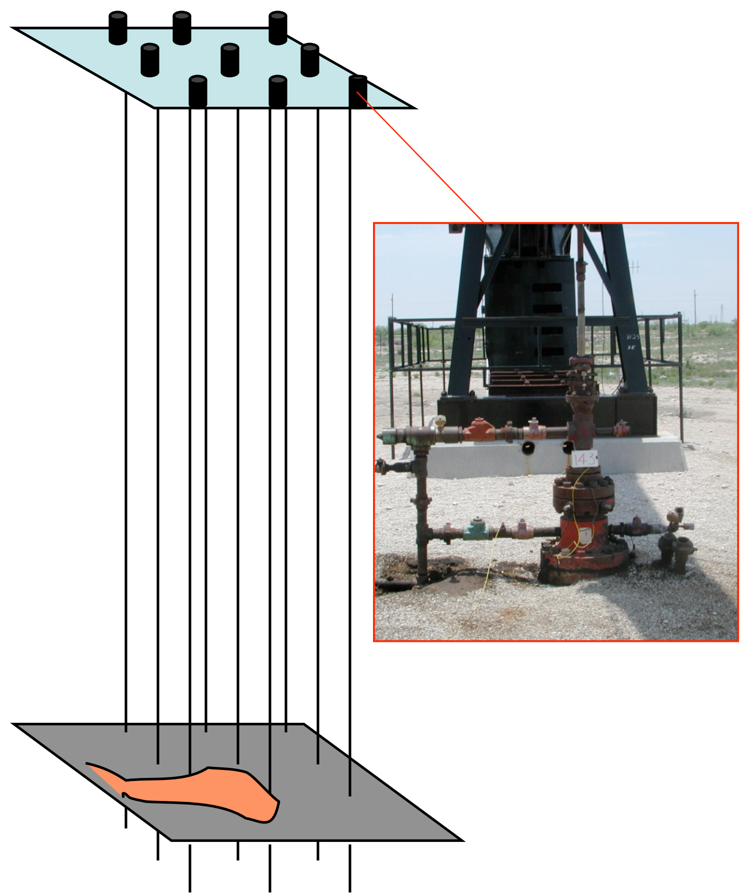


MCMC applied to CO_2 plume monitoring

Electrical resistance measurements detect changes in pore fluid resistivity





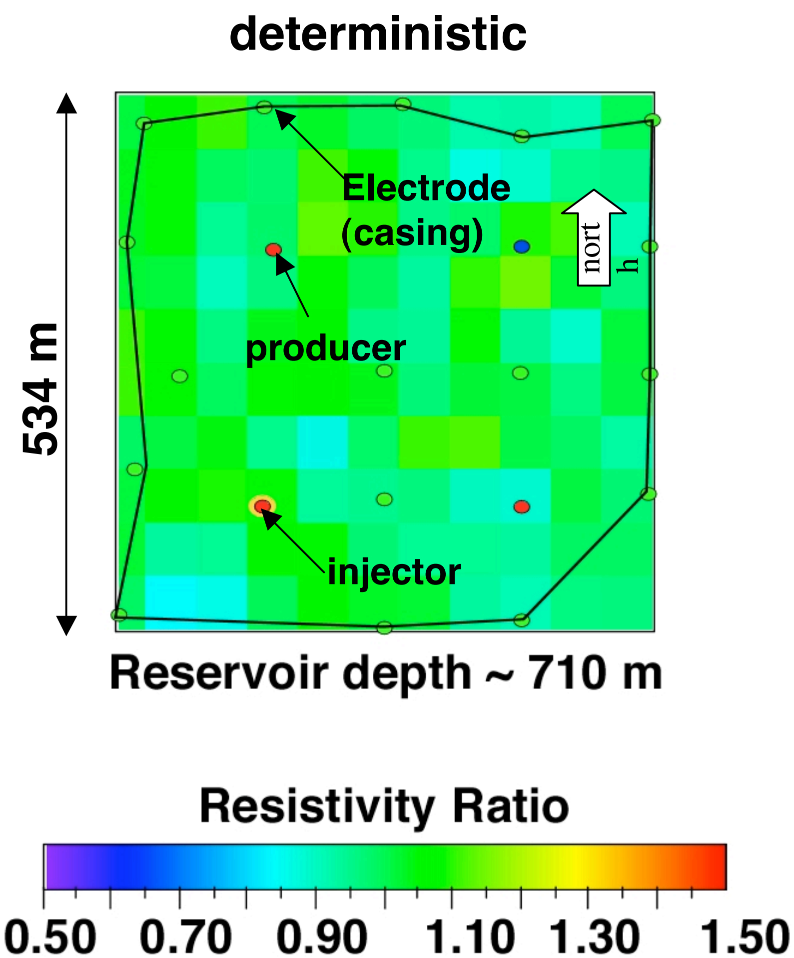


Measures resistance between electrodes

Short electrodes on casing surface of production/injection wells

Borehole casings = long electrodes
Fast, cheap, *low signal to noise*
Horizontal resolution only

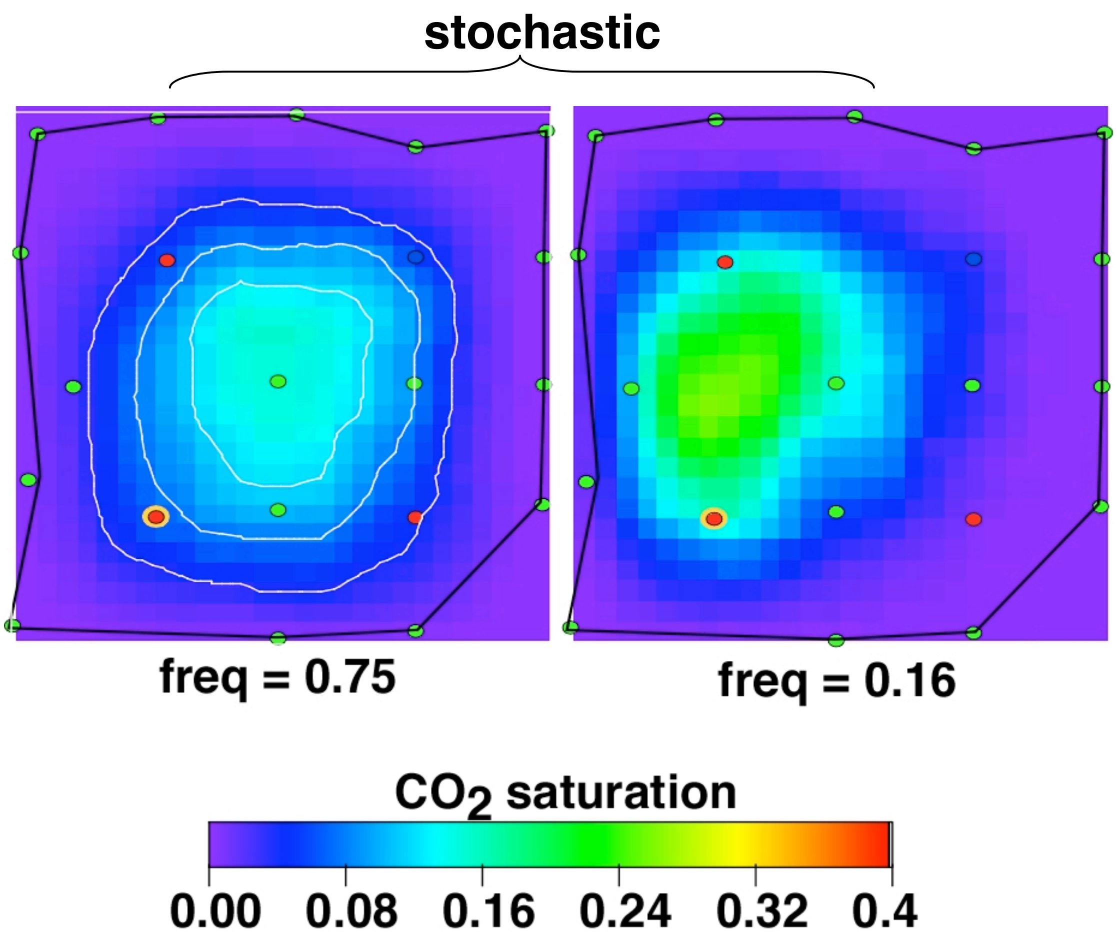
We have monitored CO_2 injection at the Salt Creek Field, Wyoming



- Used abandoned well casings as long electrodes
  - ~ 710 m deep
- Time-lapse results using deterministic approach were discouraging
- Poor signal to noise
  - ~4% of casing length in contact with reservoir

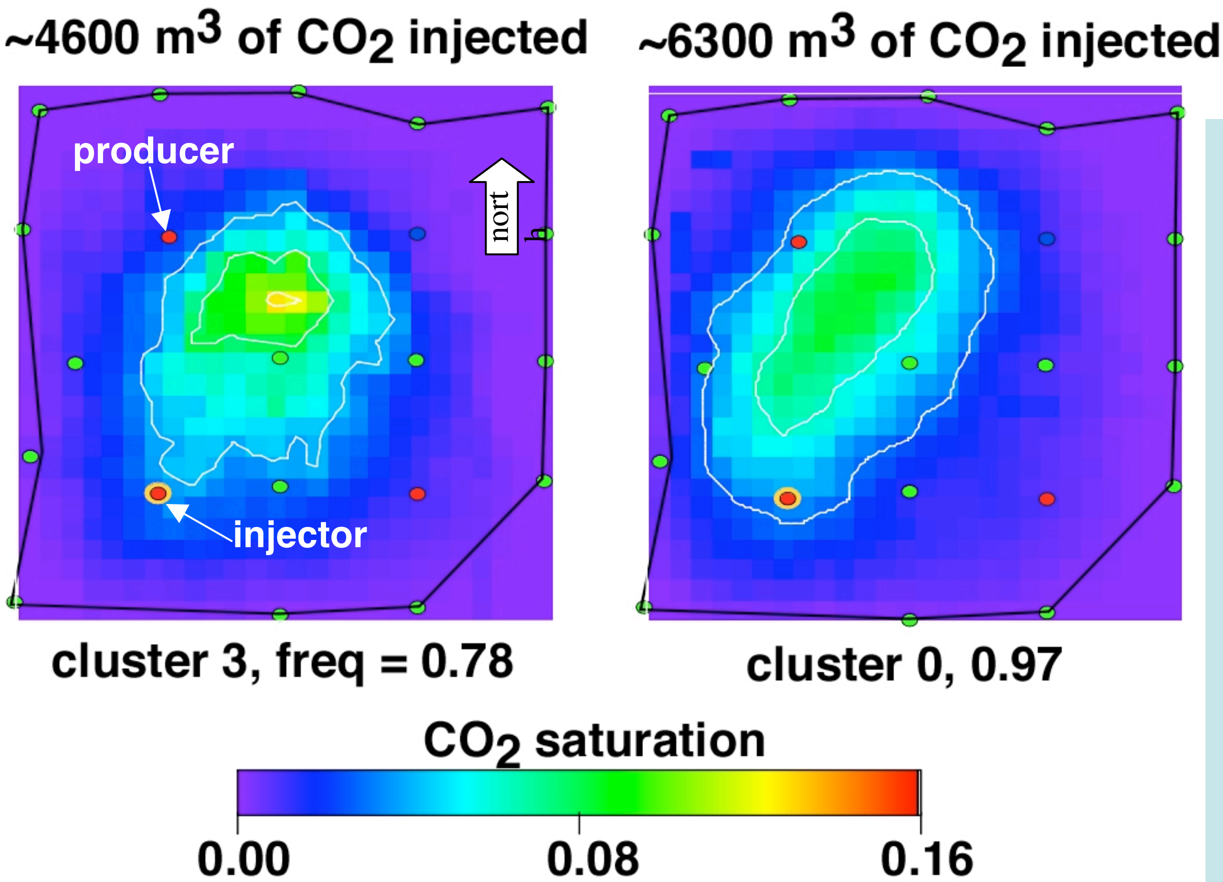
Thanks to RMOTC and Anadarko Petroleum for their support

Time-lapse stochastic inversions offered some hope



- Most frequent result is donut-shaped
  - Modeling suggests that this is consistent with poor signal to noise data
- Less frequent results show a plume starting at the injection
- Decided to use injected CO_2 volume as an additional constraint

Time-lapse sequence shows a growing CO_2 plume

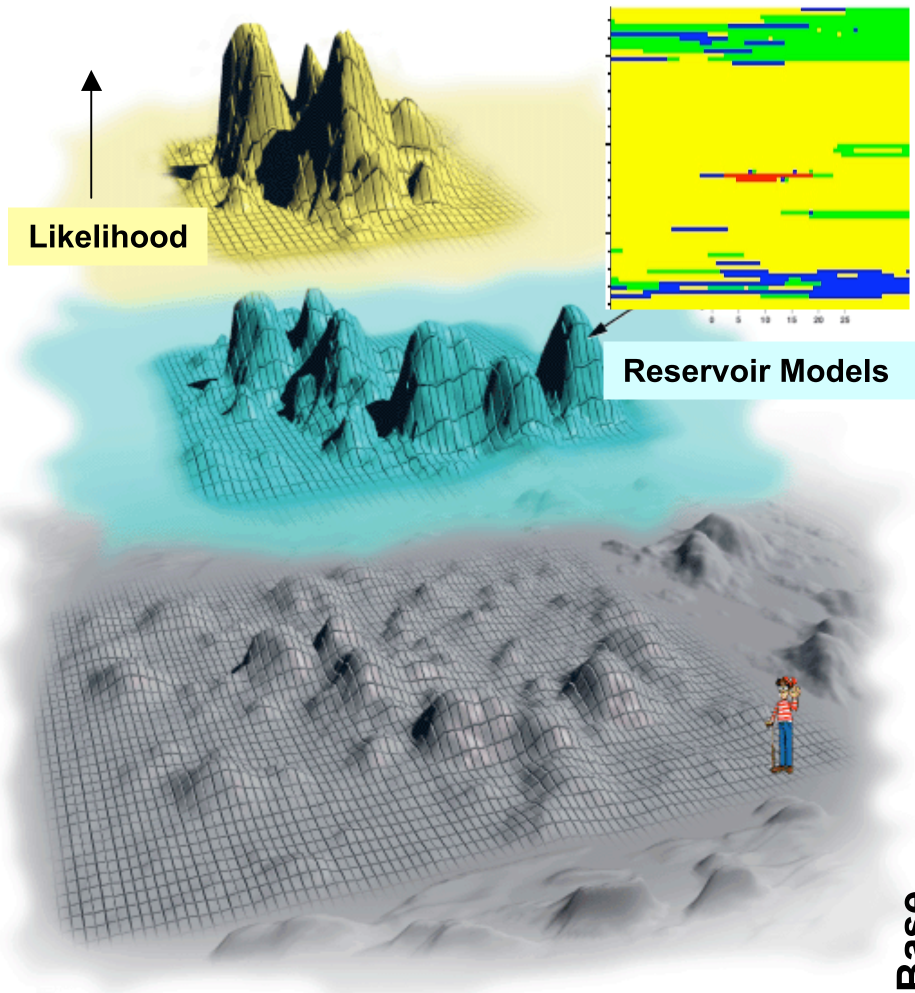


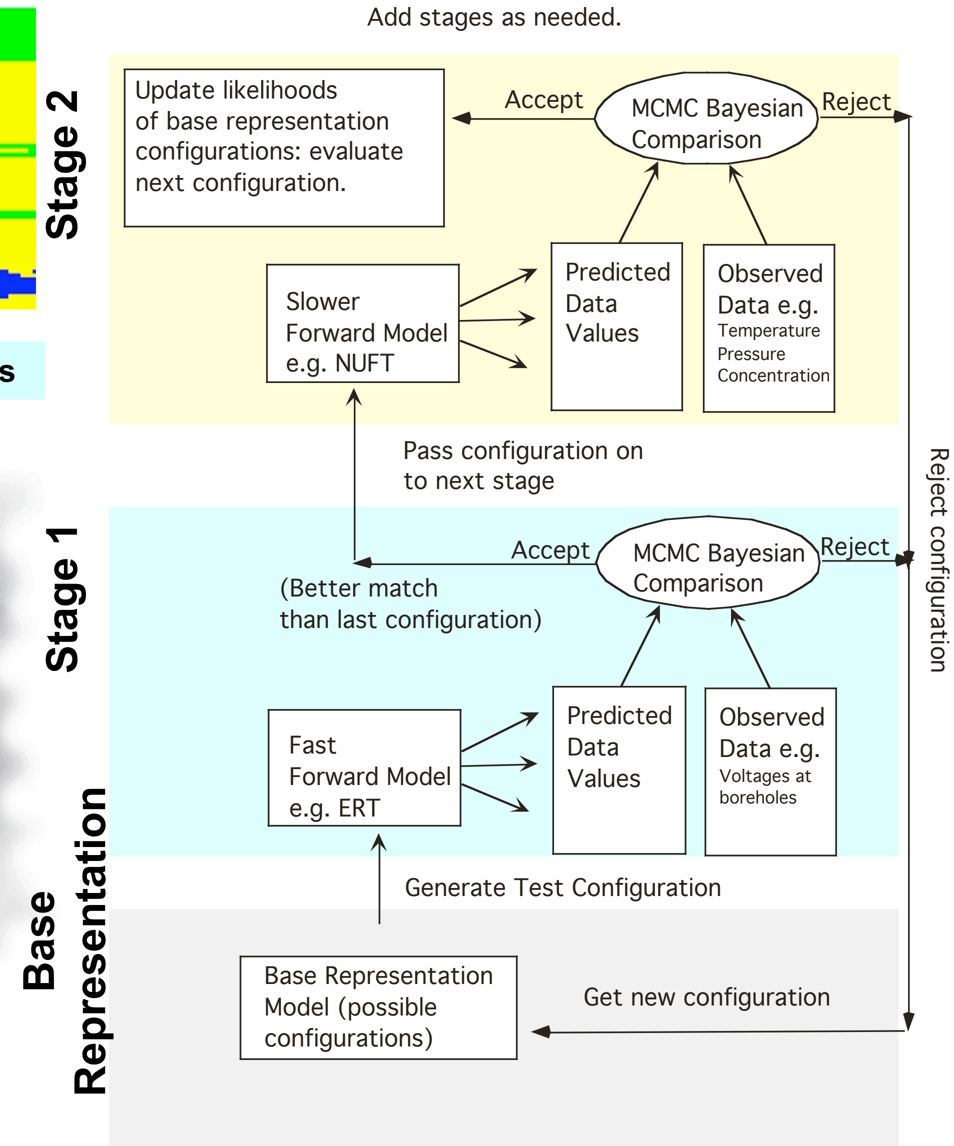
- Injected volume data helps pull out the small changes caused by the CO_2
- Confidence in the result improves when CO_2 inj. volume data is used
- Fast path established between injector and producer

MCMC can be used for site characterization and plume monitoring

- Joint reconstruction of disparate data types
- Can handle noisy data, inversions with many local minima
- Computationally intensive
  - Almost all the time is spent on the forward problem
  - Requires parallel clusters with 10's to 100's of nodes for these applications
- Models can be used for risk evaluation, identify range of reservoir performance, identify CO_2 flowpaths
- Provides rigorous measure of uncertainty in the subsurface

The Monte-Carlo Markov-Chain approach finds models consistent with all available data





Many geophysical inversions are ill-posed, non-linear , non-unique

- **Geophysical inversion is typically unstable, requires constraints**

- **Classical (deterministic) approach requires Tikhonov-type regularization for stability (e.g., minimum roughness)**

$$F(m) = \left\| D_{cal}(m) - D_{obs} \right\|_w^2 + \alpha R(m)$$

- **Statistical inversions are stabilized by a priori information**
  - **When enough information (constraints) added, problem is well-behaved (no longer ill-posed)**
  - **Prior information serves the same purpose as the regularization functional**

$$\sigma(m) = k\rho(m)L(m) \qquad F(m) = \left\| D_{cal}(m) - D_{obs} \right\|_w^2 + \alpha R(m)$$